Xenon isotopic characteristics, nitrogen and noble gas abundance patterns of two Ryugu grains

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Introduction. The JAXA-led Hayabusa2 mission returned to Earth in December 2020, carrying 5.4g of material collected during two separate touchdown operations on the C-type asteroid (162173) Ryugu. The first touchdown operation collected material from Ryugu's surface, whilst the second collected subsurface material from a crater created by an artificial impactor [1]. These samples represent the largest ever return of asteroid material to Earth, and the first from a C-type asteroid. These bodies are thought to be volatile-rich, and as such these samples provide a unique opportunity to understand volatile element processes in the solar system. Preliminary analysis of Ryugu materials suggest that it is most similar in composition to the volatile-rich CI chondrite meteorites, which may have provided a key source of volatile elements during planetary accretion [2].

The major results from the Hayabusa2 initial analysis volatile team are presented in [3]. Here, we present in further detail the results and interpretation of noble gas and nitrogen data from 2 Ryugu grains analyzed at CRPG Nancy. We focus in particular on Xe isotopic data, as well as the relationship of N to the other noble gases, as we were able to obtain full noble gas and nitrogen isotopic data from a single grain.

Sample materials and methods. At CRPG Nancy, we received 2 solid sample grains, one from each sampling site. Samples A0105-05 and C0106-06 were collected from the surface and sub-surface touchdown operations respectively [4]. Measured masses were 0.140 mg and 0.168 mg respectively. Samples were opened in a glove box to avoid atmospheric contamination and loaded into a windowed laser chamber for analysis. Gas was extracted in two steps using a CO_2 laser before introduction into an ultra-high vacuum preparation line for purification and cryogenic separation of noble gases. A sub-aliquot of the extracted gas was taken during each step for nitrogen analysis, which was purified separately using a CuO furnace cycled between 450 - 900°C and liquid nitrogen cooled cold fingers. Sample A0105-05 was analysed for He-Ne-Ar-Kr-Xe and N_2 isotopes using a Helix MC+ mass spectrometer. Sample C0106-06 was analysed for Ne-Ar and N_2 isotopes using a Noblesse-HR mass spectrometer optimised for N_2 analysis [5].

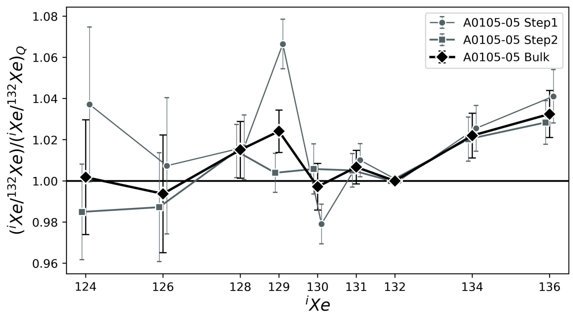

Figure 1: The Xe isotope spectrum of Ryugu grain A0105-05, normalised to ^{132}Xe and the composition of phase Q [6]. Analytical uncertainties are shown at the 1σ level.

Results and discussion

Xe isotopic composition: Measured Xe isotope results from sample grain A0105-05 is shown in Figure 1. The observed values of the light primordial isotopes (^{124,126,130}Xe) show that the Xe inventory of Ryugu is dominated by the volatile endmember phase Q [6]. Phase Q is a carrier phase of noble gases within meteorites, likely carbonaceous in nature, which is typically the most significant source of primordial heavy noble gases in chondrites [7]. There is a small excess in primordial ^{128}Xe which may record a minor contribution from an exotic volatile endmember such as Xe-HL and/or Xe-P6 (Figure 2). These components are both hosted in presolar diamonds [8].

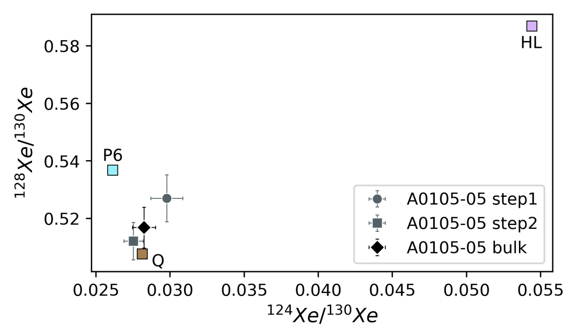

Figure 2: Primordial Xe isotope ratios ^{124}Xe/^{130}Xe and ^{128}Xe/^{130}Xe for Ryugu grain A0105-05. Plotted alongside meteoritic Xe endmembers Q, P6 and HL [7].

The low temperature extraction step records a clear excess of ^{129}Xe, produced by the decay of extinct ^{129}I [9]. Excesses in the heavy isotopes ^{134,136}Xe are also observed in both extractions, indicative of fissiogenic Xe produced from the decay of ^{238}U and extinct ^{244}Pu. Fissiogenic ^{136}Xe* abundance is 9.0 x10^{-15} molg^{-1}, which is an order of magnitude higher than that which would be expected under a closed system evolution with CI-like U and Pu abundances [10, 11]. This suggests that Ryugu either has non CI-like U, Pu abundances, or that there is an additional nucleosynthetic contribution to ^{136}Xe [12].

The ^{130}Xe abundance in A0105-05 is 1.23 (±0.02) x10^{-13} molg^{-1}. This is much higher than typical CI abundances, which are around 6.5 x10^{-14} molg^{-1} [13]. This may reflect an inherent enrichment in Q-gases compared to CI chondrites.

Nitrogen isotopic composition: Measured nitrogen isotope ratios are indistinguishable outwith uncertainty for both grains A0105-05 and C0106-06, with $\delta^{15}N$ values of +18.1 ± 0.9 and +19.5 ± 0.9 ‰ respectively. The robustness of these values is reinforced by the fact that they were measured independently on two separate mass spectrometers. These values are significantly lower than those of typical CI's, which display values around +45 ‰ [14]. Nitrogen abundances are also lower than CI values, in stark contrast to the noble gases (Figure 3).

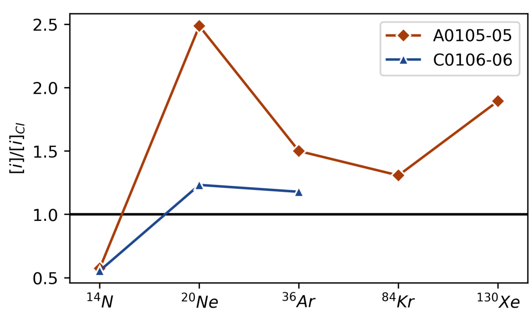

Figure 3: Measured abundances of noble gases and nitrogen in Ryugu grains measured at CRPG Nancy. Values are normalised to CI abundances [10]. Analytical uncertainties are smaller than displayed marker size.

Overall, the heavy noble gases in the Ryugu grains indeed display some similarity to CI chondrites. Yet the strong enrichment, particularly in Xe, suggests that Ryugu may represent an even more primitive, volatile-enriched reservoir that is distinct from anything observed in the meteorite record.

However, nitrogen abundances are significantly depleted compared to typical CI values, and additionally $\delta^{15}N$ is well below the CI range (Figure 4). Alongside the heavy noble gas enrichments, this suggests the preferential loss of a N-rich phase with a high associated $\delta^{15}N$.

Although both N and noble gases are concentrated in organic matter in meteorites, N is not as strongly restricted to the insoluble organic matter phases that contain Q-gases, and thus the loss of more readily soluble organic phases, potentially during aqueous alteration on the parent body, may have produced the observed volatile distribution. Whilst insoluble organic matter can be associated with localized high $\delta^{15}N$ [15], bulk phase Q has been suggested to be ^{15}N-poor, with $\delta^{15}N$ of -15‰ reported by [16]. Thus a residual enrichment in phase Q-type gases could explain the observed nitrogen depletion and isotope anomalies.

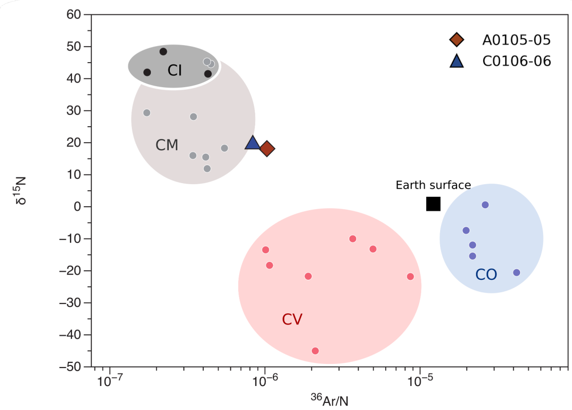

Figure 4: Plot of $\delta^{15}N$ against Ar/N for Ryugu samples alongside values for selected meteorite classes from the literature [17].

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